Development of 15 K Pulse Tube Cold Fingers for Space Applications at CEA/SBT

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ABSTRACT

Pulse tube coolers for space applications have been developed for many years at CEA/SBT. After successful developments of products in the 50 – 80 K range, our focus has changed to temperature below 20 K. Our work is based on compressors delivering about 100 W of mechanical input power to the cold fingers with a goal of several hundred milliwatts of cooling power. Most of the work performed to achieve such low temperature is based on an intercepted configuration, which permits us to focus our research on the low temperature stage. A review of the different phase shifting methods (including active phase shift and cold inertance) and the associated measured performances are presented. In parallel, studies on tube configuration and temperature at warm end have been undertaken. Experimental results are presented on a pulse tube cooler with minimum temperature below 15 K.

INTRODUCTION

Pulse tube cooler development started at CEA/SBT 20 years ago. Our focus includes both low frequency and high frequency pulse tubes. On the low frequency, two-stage pulse tube coolers providing cooling power at 4 K have been developed.[1] as well as single-stage pulse tubes optimized for temperature in the 35-50 K range. In addition to keep a strong expertise on low frequency coolers, our activity expanded to high frequency ones. For both these activities, our developments have been undertaken with the strong objective of developing new products that could be transferred to the industry or could be used in space. Indeed, two pulse tubes that provide 1 and 4 W of cooling power at 80 K are now commercialized by Thalès Cryogenics BV. For space applications, we developed with Air Liquide and Thalès Cryogenics BV, two products under ESA funding, the Miniature Pulse Tube Cooler[2] (MPTC) and the Large Pulse Tube Cooler[3] (LPTC). CEA/SBT continued its development toward lower temperature pulse tube coolers, by working on the regenerator materials and by developing a new configuration for 15 K pulse tube. This work has been supported by ESA with funding to develop new materials for the regenerator and a GSTP (ESA's General Support Technology Program) for 20 K pulse tubes. Our focus is now switching to lower temperatures, with the goal of developing 15 K pulse tubes. A foreseen need for such a pulse tube is the IXO mission, for which the precooling of J-T cooler at 15 K would allow for an efficient cryogenic chain down to 50 mK. This low temperature is necessary to allow sufficient sensitivity on the XMS instrument for X-ray spectrometry. The required cooling power at 15 K is on the order of 400 mW. In this paper we describe our latest measurements aimed at improving our knowledge of losses on the tube and how to improve overall performances of the cooler.

BACKGROUND ON PULSE TUBE COOLER

Single stage pulse tube

Our work on low temperature (below 40 K) pulse tubes started with a collaboration on an intercepted pulse tube[4] with Air Liquide. Following the first study ESA awarded Air Liquide and CEA/SBT a contract to develop 20 K pulse tube coolers. During this project, several pulse tube configurations were studied, including an intercepted pulse tube,[5] a pulse tube with a cold inertance tube and a double stage pulse tube. The results of the experiments exceeded the original goal for the breadboard models: 300 mW of cooling power at 20 K. In the favored configuration for this contract, a heat sink is required to precool the regenerator to a temperature of about 80 K. In this work, a passive precooler was envisioned for this precooling. An alternative to the use of passive precooler is the use of an active cooler, such as a LPTC cooler.

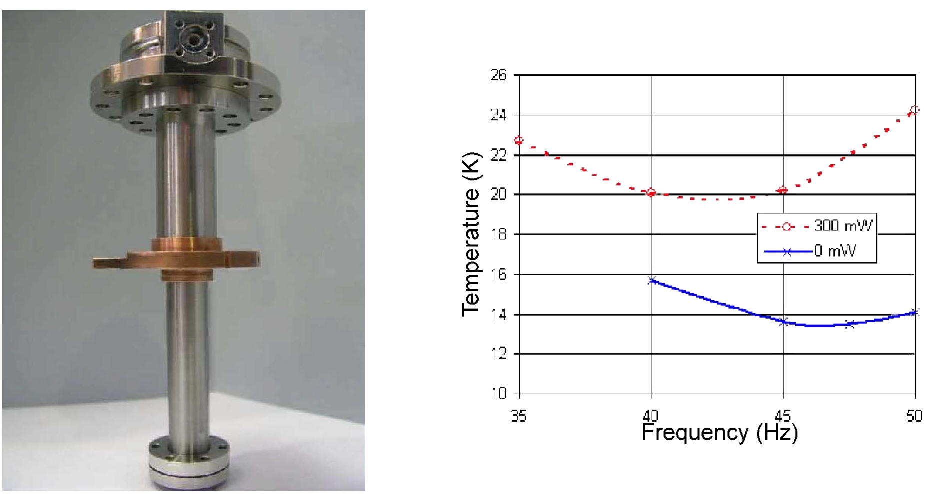
In parallel to this contract, CEA/SBT developed on internal funding a coaxial pulse tube with an intercept.[6] The cooler has been manufactured (Figure 1) and tested, showing temperature of less than 15 K with a 80 K intercept. Also, as part of this work, an active phase shifter has been used (Figure 2). Using this configuration, a temperature as low as 10.1 K has been measured.

Double stage pulse tube

Double stage pulse tubes are being developed in CEA/SBT in two directions. The first one is aimed at providing a part of a low temperature cryogenic chain: two stage pulse tubes reaching temperatures below 30 K could serve as pre cooling for a lower temperature stage. As part of this contract, more than 300 mW of cooling power at 30 K has been measured. The second direction is the development for high temperature needs (detectors, IR cooling) for which a two stage pulse tube of 70 K and 140 K has been funded partly by CNES. The focus is now on the realization of an engineering model of double stage pulse tube to achieve such a temperature.

15 K PULSE TUBE CONFIGURATIONS

Providing temperatures below 20 K with a pulse tube is a technical challenge that requires an efficient architecture and drastically limiting the source of losses. The challenge to obtain such a low temperature includes the change of properties of helium at low temperature (not a perfect gas anymore), the reduced heat capacity of the materials for the regenerator and the large variation in properties such as density of the gas inside the cooler.



(a) (b)

Figure 1. (a) Coaxial intercepted pulse tube and (b) measured temperature with a 80 K heat intercept.

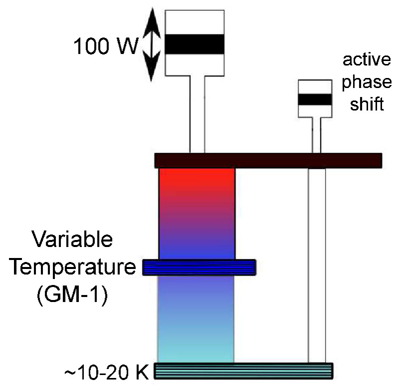


Figure 2. Pulse tube with active phase shift

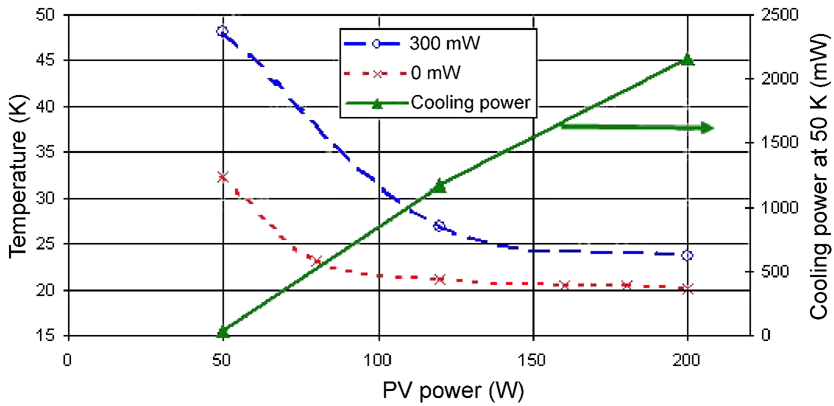


Figure 3. Thermal performances of a double stage pulse tube providing more than 300 mW of cooling power at 25 K. The cold end temperature with 0 and 300 mW of cooling power and the cooling power at 50 K are plotted as function of the input PV power.

Several configurations have been considered to develop a 15 K pulse tube. For example, NGST developed a three stage pulse tube using a combination of a two stage and a stage pulse tube.[7] Our favored approach is to couple a double stage pulse tube with a heat intercepted pulse tube. One advantage of this configuration is that the development of the last stage of the pulse tube is independent of the adjustment of the other stages. This configuration, depicted on Figure 4, is fully autonomous and does not require passive cooling or an external radiator. However, if passive shielding is available, the required input power on the compressor could be limited by the heat sinking of the first intermediary stages. The basic concept of the proposed three stage pulse tube provides the added advantage of freedom for the development of the 50 – 15 K stage of the pulse tube.

During our previous projects, we observed in our prototypes that the variation in the intercept temperature did not have an impact as strong as expected on the low temperature of the pulse tube. For our prototype with a relatively long regenerator, a gain of less than 1 K at 20 K was measured when the intercept temperature was decreased from 80 to 50 K. That seems to indicate that the limitation to achieve a lower temperature is not only the thermal gradient in the regenerator.

EXPERIMENTAL RESULTS

Before combining our work on the regenerator with our work on the 20 K pulse tube, we decided to evaluate losses due to the thermal gradient in the tube (heat conduction of the wall and heat transfer in the helium of the tube). For this study, we built a test bench with two variable

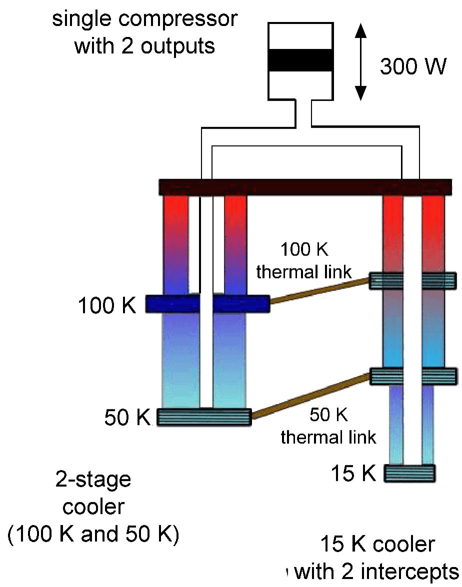


Figure 4. Three stage 15 K pulse tube: favored approach

temperatures: on the regenerator (heat intercept) and on the tube (see Figure 5). For this experiment, an active phase shift is used. The two variable temperatures are obtained thanks to the use of a thermal link with a Gifford McMahon (GM) cooler. The thermal links between the GM cooler and the heat sinks are calibrated to be used to measure the heat flows at each intercept. The resulting configuration, pictured in Figure 5, is not necessarily practical for an industrial point of view. However, it provide the opportunity to experiment with different temperatures at the pulse tube ends and allows the measurement of the effect on the cooling power achieved. In this experiment, the main driver is the 100 W pressure oscillator, and the active phase shift acts only as a phase shifter.

The results presented here represent a pulse tube using only stainless steel meshes as the regenerator material. The input power delivered to the pulse tube is 100 W; calculated by subtracting the compressor's Joule losses from the input electrical power. Some results are presented in Figure 6. These results have been done with a tube of 7.8 mm in diameter and 60 mm in length (Ø7.8 L 60).

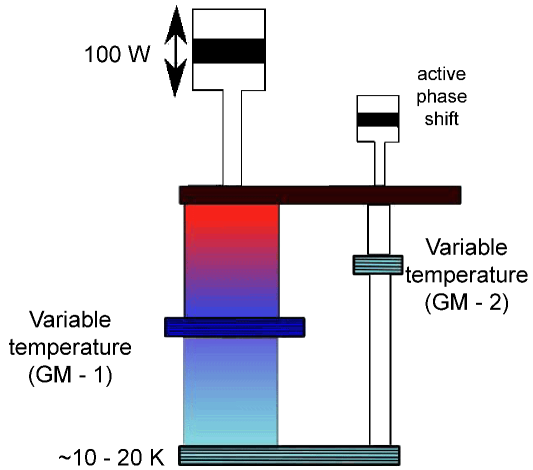


Figure 5. Test bench of a pulse tube with variable temperature tube.

In this plot, the increase of the low temperature with the increase of the warm end of the tube is clear. We analyze these plots as an estimation of the losses from the tube to the cold heat exchanger.

The conclusion from these plots is that with a tube of Ø7.8L60, a modification of the temperature of the tube from 80 to 50 K lead to a decrease in the cold end temperature of about 2 K. This corresponds to 125 mW of cooling power. This gain demonstrates the advantage of using a coaxial configuration in which the thermal gradient in the tube is modified by the heat exchange with the regenerator. These experiments are also useful in determining the optimum tube geometry to minimize heat losses.

Another experiment has been done with a longer tube (Ø7.8 L100) whose results are presented in Figure 7. It is worth noting that the heat conduction in the tube is always less than 15 mW. In the worst case (tube Ø7.8 L 60 between 80 K and 20 K) it is calculated at 13.5 mW. The testing of the longer tube will need to be completed by accomplishing a similar plot as reported for the shorter tube to evaluate the consequences of a modification of the temperature.

Our work will now focus on regenerator experiments to reduce the temperature of our cold fingers.

CONCLUSION

Our objective is to develop an efficient 15 K pulse tube. For that purpose, we proposed an architecture that permits an independent development of an intercepted pulse tube for the colder stage (50 – 15 K). Before going into the detailed design of the pulse tube, we started our development with the estimation of losses arising from the tube. We demonstrated that by changing thermal

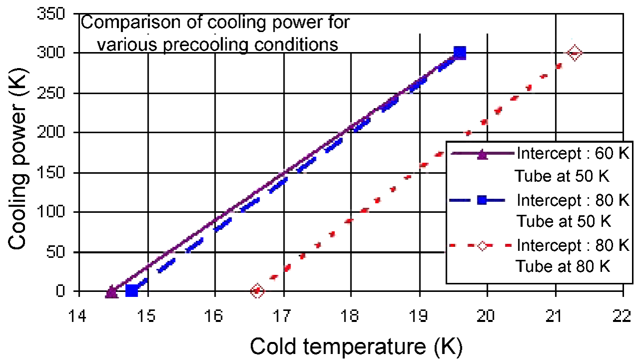


Figure 6. Test bench of a pulse tube with variable temperature tube. Tube Ø7.8L60. The temperature of the regenerator intercept and tube intercept are written in the legend as respectively ‘intercept’ and ‘tube’

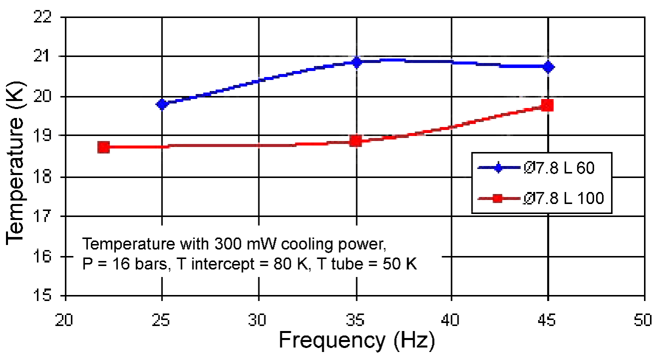


Figure 7. Comparison of temperature with 300 mW of cooling power as function of frequency for 2 different tube lengths

gradient in the tube, a gain of 125 mW of cooling power could be achieved. This work will be coupled to a previous development in which a pulse tube reached an ultimate temperature of 10 K to achieve a 15 K pulse tube able to precool a J-T cooler.

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